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Monitoring-based Commissioning: Benchmarking Analysis of 24 University Buildings in California

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INTRODUCTION

Monitoring-based commissioning (MBCx) combines building energy system monitoring with standard retro-commissioning (RCx) practices with the aim of providing substantial, persistent, energy savings [Brown and Anderson 2006]. MBCx incorporates three components: 1. Permanent energy information systems (EIS) and diagnostic tools including energy monitoring at the whole building and sub-system level; 2. Retro commissioning, based on the information from these tools and savings accounting, emphasizing measurement as opposed to estimation or assumptions; and 3. On-going commissioning to ensure efficient building operations and measurement-based savings accounting. MBCx is thus a measurement-based paradigm that affords improved risk-management by identifying problems and opportunities that are missed with periodic commissioning or basic functional testing that does not incorporate energy measurement.

There are three primary streams of additional energy savings from MBCx relative to traditional RCx (Figure 1):

1. Savings from persistence and optimization of savings from RCx thanks to early identification of recurring problems through metering and trending. Several studies have shown that RCx savings can degrade without an explicit effort to monitor and maintain them [Mills 2011, Bourassa, Piette, and Motegi 2004, Claridge et al. 2000, Piette et al. 2000].
2. Savings from measures identified through metering and trending during the initial commissioning effort, i.e., measures unlikely to be found from traditional test protocols alone. Haves, et al. [2008]

provide several examples of such measures, e.g., poor control of chilled water distribution to air handlers, unnecessary chiller operation due to disabled chiller lockout, and poor VAV zone control due to inoperative actuators on air dampers and hot water valves.

3. Continually identified new measures. With continuous monitoring, MBCx can identify new problems that emerge after the initial retro-commissioning investigation stage, such as inefficiency initiated by changes in building use, addition of new systems or processes, and changes in functional requirements that affect energy systems.

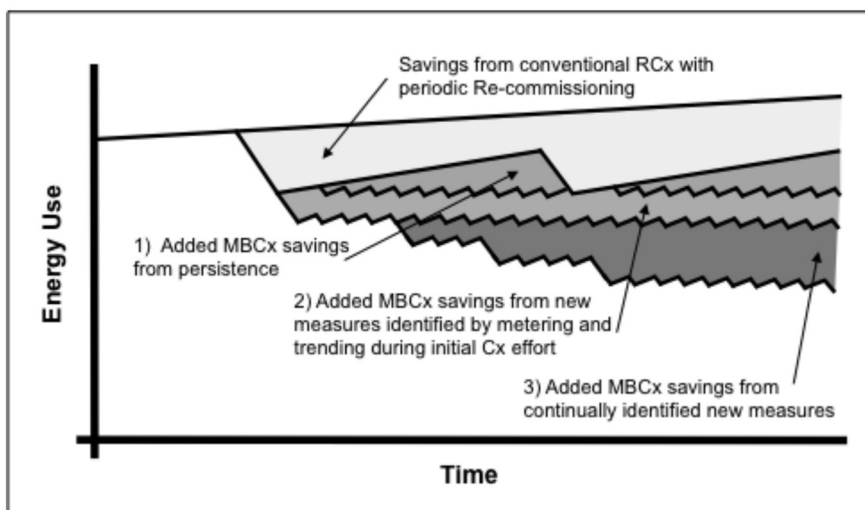


Figure 1. MBCx provides three streams of additional energy savings relative to RCx—conceptual illustration

The findings presented here are based on in-depth benchmarking of a portfolio of MBCx projects for 24 buildings located throughout the University of California and California State University systems [Mills and Mathew, 2009]. This initial set of projects was a key element of a pilot partnership with the University of California (UC), California State University (CSU), and investor-owned utilities (IOUs) for implementing energy efficiency on campuses in 2004-2005. The benchmarking analysis helped establish a permanent framework for a long-term, comprehensive energy management initiative at the 33 UC and CSU campuses served by California's four large IOUs (PG&E, SDG&E, SCE and SoCal-

Gas) (UC/CSU/IOU energy efficiency program, 2011).

Monitoring-based commissioning has its origins in 1990s work at Texas A&M (Claridge, et al, 2000) and at Berkeley Lab with the support of the California energy commission public interest energy research (PIER) Program and the California institute for energy and environment (Piette, et al, 2000; CIEE 2011). PIER and CIEE continued working to accelerate adoption of MBCx with this benchmarking effort and with other technical assistance to the UC/CSU/IOU Partnership in the form of case studies and a needs assessment, as well as description of system architectures for performance monitoring.

Thorough documentation of the success and lessons of the initial MBCx portfolio led to an ongoing program that has accumulated around \$8 million in annual savings through 2010. It is now anticipated that the program will be extended to include most major UC and CSU facilities. The program design continues to evolve as program participants become more able to exploit the benefits of extensive monitoring. California “third-party” energy efficiency deployment programs have adopted the MBCx approach for the latest implementation cycle (SCE 2009), with similar programs appearing outside California (NYSERDA 2011).

In the course of the benchmarking analysis, a quality-control/quality-assurance process for gathering and evaluating raw data from project sites was developed, and then a number of metrics were selected to use for project benchmarking and evaluation, including: appropriate normalizations for weather and climate; accounting for variations in central plant performance; and consideration of differences in building types. A cost-benefit analysis of the resulting dataset was performed, including comparisons to projects from a larger commissioning database.

ANALYSIS APPROACH

Buildings in the MBCx cohort were analyzed and compared. In the pilot phase of the UC/CSU/IOU Partnership, special effort was made to maintain a set of projects that included just commissioning measures with no equipment upgrade (retrofit components). This was intended to isolate the impact of commissioning measures and allow evaluation of the MBCx approach. In addition, the cohort as a whole was compared to the outcomes of other retro-commissioning projects that have been analyzed as part of the Lawrence Berkeley National Laboratory database

of commissioning and retro-commissioning costs and benefits. This is referred to as the “meta-analysis” (Mills, et al, 2004; Mills 2009).

This meta-analysis normalizes diverse retro-commissioning data to standard energy prices, and corrects for inflation so that projects costs and savings in various years can be more accurately compared. To use meaningful peer groups for benchmarking and analysis purposes, the following conventions and normalizations were adopted:

- **Building types:** To distinguish among service levels, separate analyses were conducted for laboratory facilities and other facilities that were less energy intensive.
- **Weather and climate:** Weather-normalization was achieved by short-term monitoring of energy and actual weather, then scaling to annual values based on normalization per long-term data. For climate normalization, non-laboratory MBCx projects were compared to other retro-commissioned projects in the states of California, Oregon, and Washington. This primarily excludes the meta-analysis projects that are in high-humidity or severe cold climates. Due to lack of data from CA/OR/WA climates, for laboratory-type spaces, those in the MBCx sample were compared to other labs wherever they occur in the U.S.
- **Central plant utilities:** reported (i.e. “actual”) efficiency rates were used for plant utilities.
- **Economics:** standardized commercial energy prices were used, and all cost data were inflation-corrected to 2007 levels.

ENERGY USE, COSTS, AND SAVINGS

Table 1 and Figure 2 present the benchmarking analysis of various energy use, cost and savings metrics. The analysis includes comparison to the meta-analysis. For the MBCx cohort, source energy* savings of 24 kBtu/ft²-yr (11%) were achieved, with a range of 2-25%. Median electricity savings were 1.6 kWh/ft²-yr (7%), with a range of 1.0-17%. Peak

*Source energy is the total amount of raw fuel that is required to generate and transmit electricity, natural gas and other forms of energy to the building. It incorporates all transmission, delivery, and production losses. Source energy is a more equitable way to add primary (e.g. natural gas) and secondary (e.g. electricity, district chilled water) types of energy supplied to a facility.

electrical demand savings were 0.2 W / ft²-yr (4%), with a range of 3-11%. It is worth noting that these savings numbers are based on a greater degree of measurement than is typically found in efficiency project savings accounting.

The aggregate commissioning cost for the 24 projects (26 buildings; 3.4 million square feet) analyzed was \$2.9 million. Costs ranged from \$0.37-1.62 ft², with a median value of \$1.00 for buildings that implemented MBCx projects. Half of the projects were in buildings containing complex and energy-intensive laboratory space, with the higher costs associated with these projects. New or upgraded whole-building energy metering, sometimes including chilled water, hot water and/or steam metering also added to costs. Median energy cost savings were \$0.32/ft²-yr, for a median simple payback time of 2.5 years. Thus, significant and cost-effective energy savings were obtained. The greatest absolute energy savings and shortest payback times were achieved in the subset of laboratory-type facilities. It should be noted that the costs shown include initial costs to install metering equipment. The metering is permanently installed so these are one-time costs; however, additional costs will exist if third-party Cx services are used for the analysis. These ongoing costs can be reduced or eliminated if the building operators are properly trained in how to interpret and act upon the data, in which case no ongoing third-party Cx services are needed.

The outcomes for the MBCx cohort were compared with those for the LBNL meta-analysis, disaggregating the analysis by climate and building type (Figure 2). The disaggregation of impacts highlights the importance of the examination of peer groups. Although small in number, the more energy-intensive buildings skew most values upwards for the all-inclusive sample.

Across the MBCx sample, permanent monitoring costs were a much higher proportion of the total than for the comparison group, representing 40% of total. Some projects in the national meta-analysis sample also involved a degree of monitoring (up to 47%, characterized as “verification and persistent tracking”), but the median value for the 30 meta-analysis projects for which data are available is only 2%.

The high metering cost fraction for the MBCx program is per program design. Sites that hosted the UC/CSU MBCx program tend to be thinly metered, as they are usually on campuses that are centrally metered, with individual buildings often not having the building-level metering emphasized by the MBCx concept.

Table 1. Benchmark outcomes for meta-analysis (MA) and monitoring-based commissioning (MBCx) for full samples and for climate- and building-type cohorts (median values). [Mills and Mathew, 2009]

Max	All Sites			By Climate			By Building Type		
Sample	MA*	MBCx**		MA - non-Lab	MBCx - non-Lab		MA - Lab	MBCx - Lab	
Location	US	CA		CA/OR/WA	CA		US	CA	
Number of projects	84	21		36	14		13	12	
Number of buildings	128	26		72	9		15	12	
Median building size (square feet, sf)	154,000	121,214		197,953	117,607		139,361	106,592	
Total Source Energy									
Pre-cx (kBtu/sf-yr, source)	323	335		231	189		543	534	
Savings (kBtu/sf-yr, source)	31	24		15	18		119	40	
Savings (%)	12%	11%		9%	10%		16%	12%	
Building Electricity									
Pre-cx (kWh/sf-yr)	23	21		16	14		29	35	
Savings (kWh/sf-yr)	1.7	1.6		1.2	0.9		1.5	1.7	
Savings (%)	8%	7%		9%	8%		5%	6%	
Building Peak Power									
Pre-CX	4.2	3.7		4.2	2.7			4.4	
Savings	0.5	0.2		0.1	0.3			0.2	
Savings (%)	2%	4%		9%	8%			3%	
Building Fuel									
Pre-cx (kBtu/sf-yr, source)	89	153		89	50			195	
Savings (kBtu/sf-yr, source)	7	12		3	2			20	
Savings (%)	9%	7%		5%	5%			10%	
Central Thermal***									
Pre-cx (kBtu/sf-yr, source)	227						388		
Savings (kBtu/sf-yr, source)	56						142		
Savings (%)	32%						24%		
Central Hot Water									
Pre-cx (kBtu/sf-yr, source)		42			19			68	
Savings (kBtu/sf-yr, source)		8			8			16	
Savings (%)		25%			36%			23%	

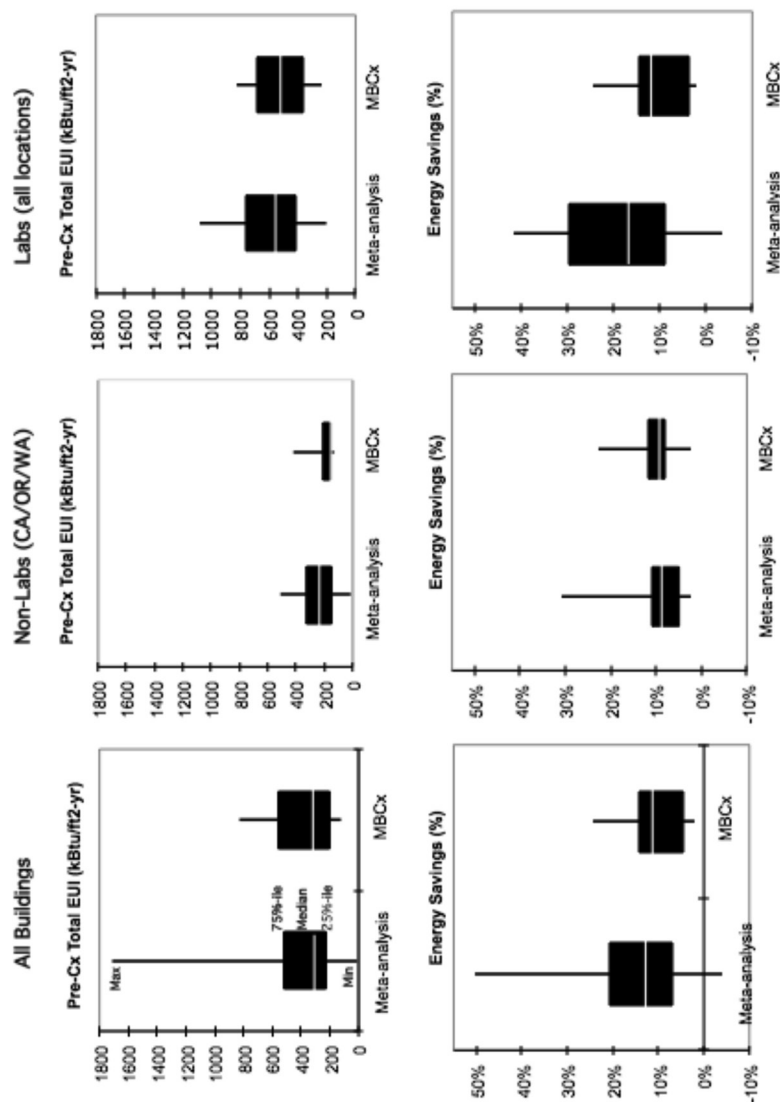


Figure 2a. Portfolio comparison of MBcX and meta-analysis in terms of pre-Cx source EUI (energy use intensity), source energy savings percentage, project costs, and payback times for three cohorts: all buildings (left column); non-lab buildings in CA/OR/WA (middle column); labs in all locations (right column).

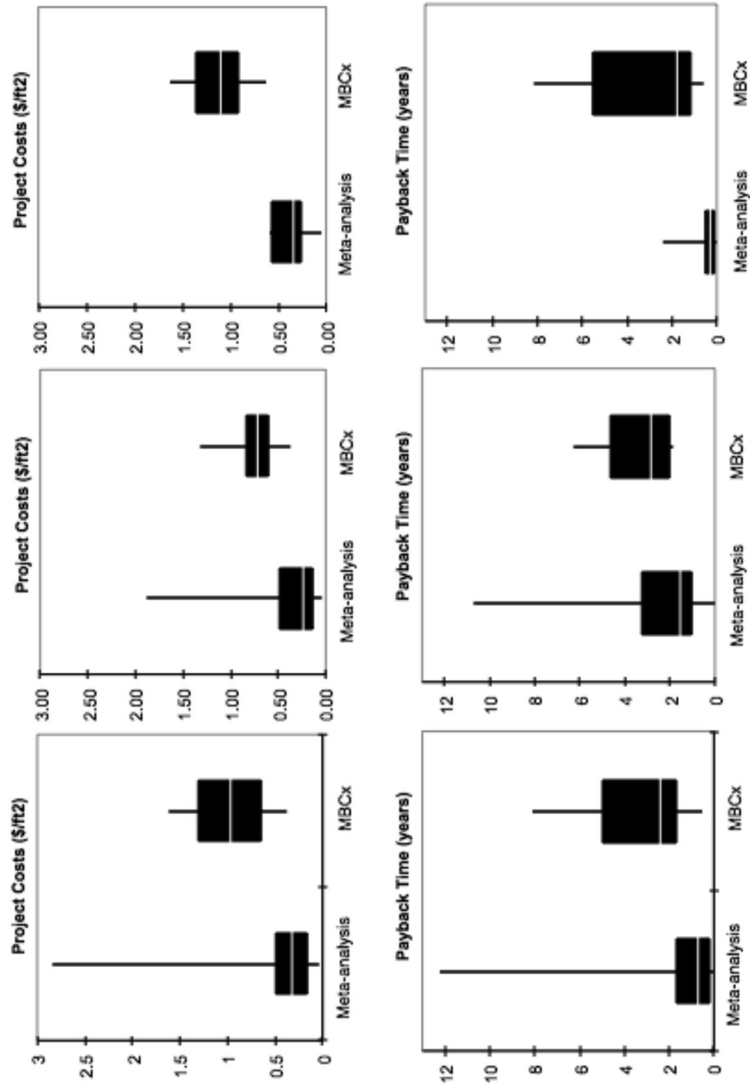


Figure 2b. Portfolio comparison of MBCx and meta-analysis in terms of pre-Cx source EUI (energy use intensity), source energy savings percentage, project costs, and payback times for three cohorts: all buildings (left column); non-lab buildings in CA/OR/WA (middle column); labs in all locations (right column).

Thus, particularly high investments in new or upgraded metering were required at these sites, including whole-building energy metering. In addition, many of the campuses have chilled water, hot water, and/or steam distribution systems. Building-level metering ("BTU meters") for these energy streams has significant costs that are higher than for stand-alone buildings (e.g., steam or hot water metering can be more expensive than gas metering, chilled water metering is in addition to electricity metering). Energy monitoring capability is providing additional value in the more recent years of the program, as the basis for program incentive payments has shifted from targeted savings to actual measured savings.

Training for campus staff is another cost component intended to ensure persistence in savings. Program partners continue to see the value in cost components aimed at obtaining persistence in savings. The Program depends on these up-front components for long-term savings as the basic program framework still reflects the traditional retrofit program design with a short window for savings accounting.

DEFICIENCIES AND INTERVENTIONS

A framework was applied for tabulating the deficiencies identified and the corresponding commissioning measures implemented to correct them. This framework was previously used in the LBNL meta-analysis with refinements and clarifications for the present version. Various metrics can be used to characterize deficiencies and measures. These include: total number, number normalized by floor area, and occurrence by percentage of buildings.

A total of 1120 deficiency-measure combinations were identified in the course of commissioning the 24 UC/CSU projects described in this article (see Table 2). The most common locations of deficiencies were in: HVAC (combined) (65% of sites), air handling and distributions systems (59%), cooling plant (29%), heating plants (24%), and terminal units (24%). The most common measures were adjusting set points, modifying sequences of operations, calibration, and various mechanical fixes (each done in about two-thirds of the sites). The floor area-normalized rate of occurrence of deficiencies and corresponding measures ranged from about 0.1/100ksf to 10/100ksf, depending on the issue (Figures 3 and 4).

Table 2. Deficiencies and measures in MBCx projects

		Commissioning Measures Implemented																SUM												
		Design, Installation, Retrofit, Replacement				Operations & Control								Maintenance																
Component being Commissioned	Design change	Installation modifications	Retrofit/equipment replacement	Other	OC1	OC2	OC3	OC4	OC5	OC6	OC7	OC8	OC9	Calibration	Mechanical fix	Heat transfer maintenance	Filtration maintenance	Other	SUM											
					Implement advanced reset	Start/Stop (environmentally determined)	Scheduling (occupancy determined)	Modify setpoint	Equipment staging	Modify sequence of operations	Loop tuning	Behavior modifications/manual changes to operations	Other																	
					D1	D2	D3	D4	0	11	9	12	47							0	29	17	0	0	97	123	0	7	0	357
					V	2	2	1	0	11	9	12	47							0	29	17	0	0	97	123	0	7	0	20
					C	1	1	0	0	2	4	0	1							2	2	2	0	2	2	0	0	1	1	35
					H	0	2	1	1	1	3	1	9							6	1	1	0	0	1	6	0	0	2	191
					A	0	0	6	1	30	2	17	12							9	23	4	0	2	29	38	9	9	0	162
					T	0	0	0	0	0	0	0	5							0	6	5	0	0	136	10	0	0	0	342
					L	1	1	1	0	1	286	49	0							0	0	0	3	0	0	0	0	0	0	3
					E	0	0	0	0	0	0	0	0							0	0	0	3	0	0	0	0	0	0	3
					P	0	0	0	0	0	0	0	0							0	0	0	3	0	0	0	0	0	0	3
Facility-wide (e.g. EMCS or utility related)		F	0	0	0	4	0	0	0	0	0	0	3	0	0	0	0	0	7	0										
Other		O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
SUM		4	6	9	6	45	304	79	74	17	61	29	9	7	265	177	9	16	3	1120										

The choice of metric is important. For example, while a very high number of lighting-related deficiencies were identified (and a correspondingly high number per unit floor area), they were found in a relatively small fraction of all sites, just over 10%. Most of the lighting deficiencies were related to scheduling. Conversely, while the number of deficiencies in heating and cooling plants was a small fraction of the total, they were relatively common (being found in 25-20% of sites).

Three examples of how MBCx helped identify and address deficiencies

When tied to an Energy Information System, previously ignored electric and gas meters revealed inefficient nighttime operation, simultaneous heating and cooling, and excessive lighting. New scheduling programs resulted in nighttime energy savings.

When the existing electric and gas meters at the building in project #12 were tied into the campus energy management system and their energy use was trended, high nighttime electricity and natural gas use were immediately obvious. Further investigation revealed that the air handlers operated continuously—although the building was empty at night. The chiller also operated at night, as well as the boiler, performing unintended simultaneous heating and cooling. Much of the lighting was also found to operate after hours. Once identified, the nighttime operations were easily addressed by reprogramming the EMS.

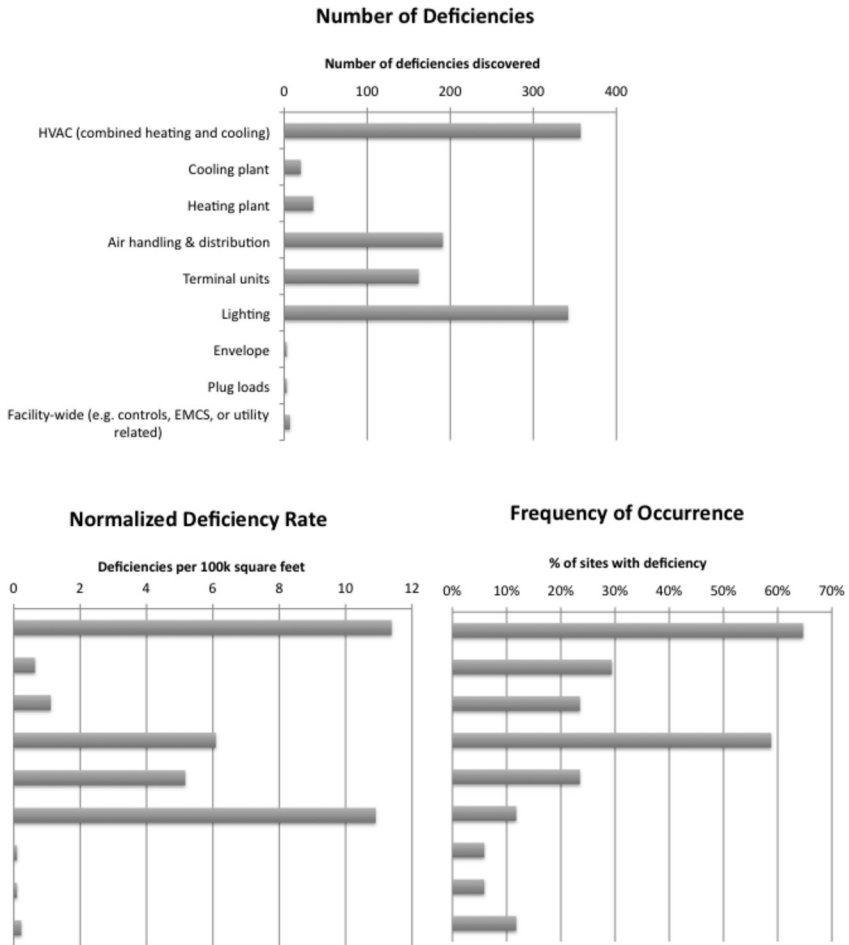
The building has had electric and gas meters for a number of years. If the meters were manually read monthly, the total usage readings apparently had not triggered any concern, and would not have revealed the simultaneous heating and cooling. This seemingly obvious problem was not identified until the MBCx monitoring was in place.

The MBCx project also included installation of a Btu meter on the hot water output of the building boiler. The readings from this meter revealed that the calibration factor used for the gas meter was not properly corrected for gas pressure. All the historical gas meter readings were incorrect. The new gas readings that are based on the correct multiplier now compare properly with the metered hot water use.

Temperature sensors reveal faulty thermostats, broken VAV actuators; planned chiller upgrade deemed unnecessary.

The building in project #08 has 28 zones served by rooftop units and a single boiler and chiller. VAV RH boxes control zone temperatures using pneumatic thermostats and actuators. The presence of pneumatic controls means there was no monitoring available for temperatures in the spaces, VAV box airflow, or reheat coil position.

Figure 3. Frequency of deficiencies found through MBCx



The MBCx project installed temperature sensors in multiple rooms in the building that were tied back into an energy management system. Large variations in temperatures were identified in the trended data for the various rooms. One room might be 79°F, while another similar room was 70°F. This led to an investigation of the pneumatic thermostats and VAV boxes. Roughly 80% of the zones were found to not be controlling temperature properly. A number of thermostats were found to be out of calibration. A number of VAV boxes were found to have inoperative actuators on the air dampers or hot water valves. There was a significant amount of un-

productive energy use in heating, cooling and distributing air unnecessarily. Discomfort in the building led to the chillers' being manually started during some hours when comfort could have been maintained without chilled water, if given properly operating zone controls. The controls were calibrated and any malfunctioning actuators were replaced when possible. The recommendation was made to convert to direct digital controls at the zone level in the future.

A project under consideration was the replacement of the chiller with a more efficient unit. The metering determined that the annual load on the chiller was lower than expected and that it was likely to be lower still after repair of the zone controls. As a result, it was determined that there was inadequate annual energy use to justify the replacement of the chiller on the basis of energy savings.

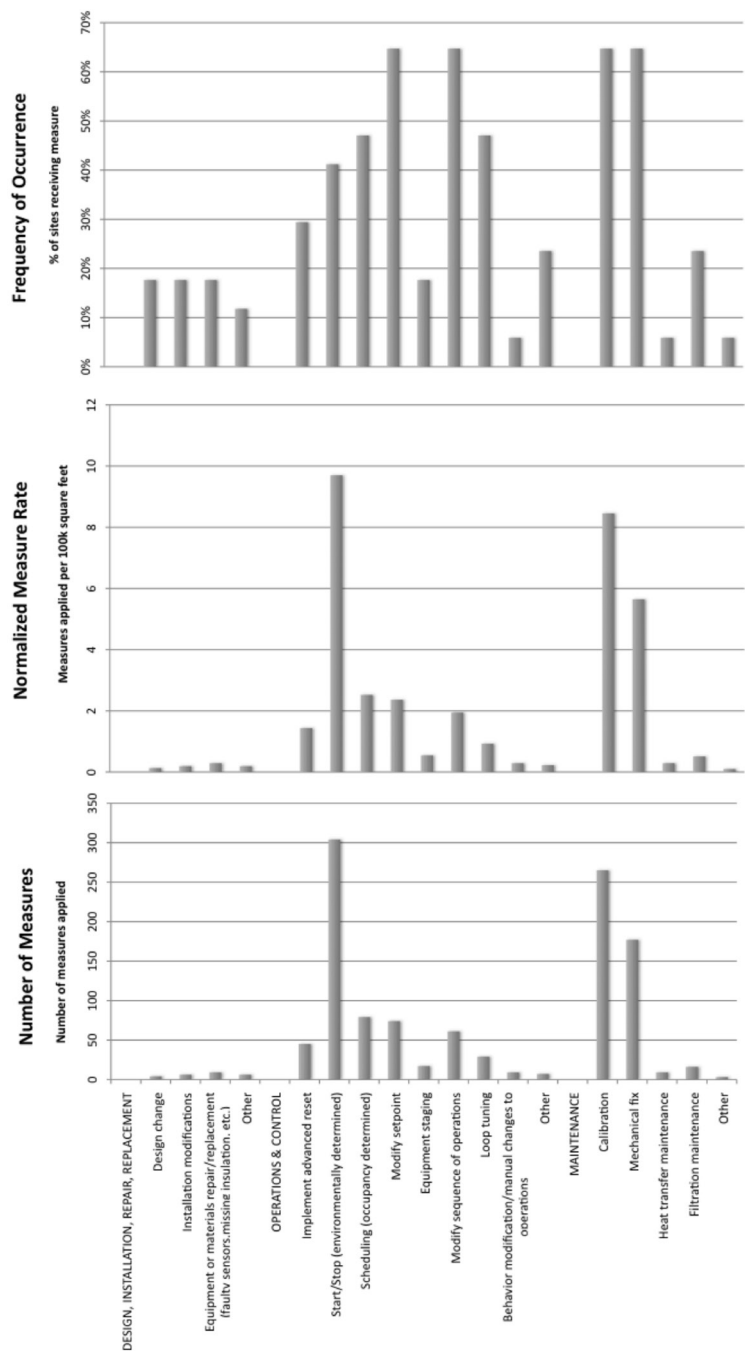
Data trending uncovers non-delivery of chilled water. Comfort improved and energy was saved.

The MBCx team for project #03 trended all of the points available on the building management system. The evaluation of data from the first air handler identified supply air and chilled water temperatures outside of the expected performance range. The campus team investigated and found that chilled water from the central plant was not being drawn into the building loop. As a result, the building air handlers were delivering air at an elevated temperature, causing them to operate at high speeds to meet the cooling load of the building. The team modified the set points on the loop pressure control and the VFD controller, resulting in a proper air handler supply air temperature and an appropriately high chilled water temperature returning to the campus loop. The metering system observed a reduction in the building electric load and an increase in the building chilled water load. The effect of the increased load on the chiller plant was calculated to offset only about 20% of the fan savings. The increased chiller electricity use occurred at night because the campus used a thermal energy storage system at the central plant. This is an example of the analysis of trended building energy performance data leading directly to reduced energy use at the building as well as increased comfort.

CONCLUSION

Buildings rarely perform as intended, resulting in energy use that is higher than anticipated. Monitoring-based commissioning can identify problems and opportunities that are missed with conventional

Figure 4. Frequency of measures implemented in MBCx projects



approaches. While impacts vary from project to project, on a portfolio basis, MBCx is becoming accepted as a cost-effective means of obtaining significant program-level energy savings across a variety of building types. For the 24 projects that were analyzed, costs ranged from \$0.37 to 1.62/Ft², with a median value of \$1.00 for buildings that implemented MBCx projects. Median simple payback time was 2.5 years and median source energy savings was 11%. Thus, significant and cost-effective energy savings were obtained compared to typical commissioning projects, despite the additional investment in permanent metering equipment. The greatest absolute energy savings and shortest payback times are achieved in the subset of laboratory-type facilities. Energy savings are expected to be more robust and persistent over time for MBCx projects than for conventionally commissioned ones, but this is difficult to confirm as current energy efficiency deployment program design is still not usually conducive to long-term verification of savings. The permanently installed monitoring equipment used in MBCx becomes an enabler for ongoing or repeat Cx activities, helping find new opportunities and guarding existing savings from backsliding. MBCx thereby represents an important risk-management strategy to ensure verifiable and durable energy use reductions. The increased deployment of smart meters and energy information systems will further support the wider use of MBCx as routine practice and more broadly demonstrate the value measured data as a basis for commissioning activities.

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